PLUTO STRUCTURE AND COMPOSITION: EVIDENCE FOR A SOLAR NEBULA ORIGIN; William B. McKinnon[1] and Steve Mueller[2], [1]Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Saint Louis, MO 63130; [2]Department of Geological Sciences, Southern Methodist University, Dallas, TX 75275.

The radii of Pluto and its satellite Charon and their combined mass have recently been precisely determined: 1122.7 ± 3.5 km for Pluto and 599.7 ± 5.8 km for Charon, with a mean density for the system of 1.991 ± 0.018 g cm^{-3} (1-σ formal errors) [1]. Despite the similarity of this density to that of Ganymede (1.94 g cm^{-3}) and Callisto (1.86 g cm^{-3}), Pluto is not like these objects. It is a new kind of world, intermediate in size between the largest medium-sized icy satellite, Titania (800-km radius), and the smallest icy Galilean satellite, Europa (1569 km). Suffering less self-compression than Ganymede or Callisto, it is considerably more rock-rich than these two bodies, and structurally its closet cousin is Europa. Although the individual masses of Pluto and Charon are not yet known, making the reasonable assumption that Charon's density lies between 1 and 3 g cm^{-3} places Pluto's density in the range 1.84 - 2.14 g cm^{-3}. Using these minimum and maximum density values, we construct structural models for Pluto using the methods of [2]. Of the mineralogical models for rock components of outer solar system objects in [2], we choose "carbonaceous chondrite" (hereafter CI-rock) to represent the rock in undifferentiated models and "Prinn-Fegley rock" (hereafter PF-rock), a less water-rich theoretical condensate [3], to represent the rock in the cores of completely differentiated models. The STP density of CI-rock is 2.766 g cm^{-3} and that of PF-rock is 3.262 g cm^{-3}. The CI-rock density is high because it does not include the ~10 wt% organic "residue" of CI chondrites; we treat this as part of the ice component (i.e., it obeys the ice EOS).

The first suite of models takes the ice component to be solely water-ice. Temperatures are chosen to represent two extremes: "hot" models possess core temperatures of 1000 K, and ice or unmixed ice-rock temperatures are always 5 K less than the ice melting temperature at the appropriate pressure; "cold" models are 130 K everywhere. The temperature dependence of our results are small, however. An undifferentiated Pluto should have an ice VI center and a central pressure in the range 0.63 - 0.87 GPa. A differentiated Pluto should have a higher central pressure, between 1.1 and 1.4 GPa, a large silicate core, and a pure ice I mantle 210-310 km thick. Differentiation causes an ~4% increase in radius.

Perhaps our most important results are estimates of Pluto's rock fraction, or more specifically, the rock/(rock + H_2O-ice) mass ratio. These range from 0.67 to 0.80 for undifferentiated models with the minimum and maximum density (expressed in terms of CI-rock) to 0.69 to 0.79 for differentiated models (expressed in terms of PF-rock). Variability due to temperature is about ± 0.01. Rock volume fractions for the undifferentiated models range between 0.40 and 0.56. These values are just shy of the ~ 60% necessary for convective self-regulation of Pluto's internal temperature to break down [4]. Even so, if Pluto underwent even minimal differentiation during accretion or during Charon's formation, which may have involved a large-body impact [e.g., 5], then it is unstable to further differentiation by means of the "accretional trigger" (multiple thermal boundary layers) of [2]. In Pluto's case, the extra thermal boundary layers, at the interface between a pure ice upper mantle and an undifferentiated lower mantle, are all in the ice I field and melting in the ice-rock lower mantle is always relatively easy to initiate. Thus, although Pluto could be undifferentiated (in bulk), it is most likely a differentiated object.

A comparison to Ganymede and Callisto is instructive. The uncompressed density of a differentiated Pluto is within a percent of the bulk value estimates. The maximum values for Callisto and Ganymede, for differentiated models, are ~ 1.53 - 1.58 g cm^{-3}, significantly smaller. Unless Pluto *is* undifferentiated and close to minimum density, it is considerably enriched in silicates compared to all icy satellites save

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Europa. The Pluto rock fractions given above are in fact minimum estimates. They count organic matter as part of the ice fraction (which *is* appropriate for calculating volume fractions that affect viscosity or uncompressed density). From a cosmogonic point of view, the corrected mass fractions are ~ 0.73 - 0.86 (!) for differentiated and undifferentiated models. In addition, Pluto has a methane surface of uncertain depth. Adding a cool. low-density methane layer to the models drives the rock/(rock + water-ice) mass fraction up by about 1.7% per 10 km of methane for fully differentiated models and 3.1% per 10 km for undifferentiated ones. Clearly, Pluto's high rock/ice ratio is a fundamental clue to its origin. We consider four explanations.

(1) Pluto formed in the inner solar system. This concept goes back to erroneous ideas that Pluto is composed of impossibly dense materials. In this case, however, an explanation as to how Pluto acquired its non-negligible ice component *and* satellite is lacking. It is, of course, far-fetched that an object would be scattered into the outer solar system only to be trapped in a stable resonance with Neptune while there are plenty of local objects to be captured.

(2) Pluto lost volatiles during accretion. Ahrens and O'Keefe [6] proposed that Ganymede and Callisto preferentially lost water ice due to impact vaporization, thereby increasing satellite rock/water-ice ratios from the ~40/60 cosmic value. Because satellite formation times are rapid, Stevenson *et al.* [7] prefer a scenario in which interaction with the proto-Jovian nebula allows steam to escape back into it. The mechanism of [6] fails for Pluto because infall velocities are low (<1 km s^{-1}; see their Fig. 5). Any proto- Uranian or Neptunian nebula was also probably too cold for the scheme of [7]. This is another argument against the generally discredited theory that Pluto is an escaped satellite of Neptune.

(3) Pluto lost volatiles during the large-body impact that created Charon. This is not evaluated here, but it is worth noting that, with such low-mass objects, the collision that could have created a binary pair would be a low velocity one [e.g., 8]. Whether enough icy material could be scattered out of the resonant phase space should be carefully studied.

(4) Pluto is a large outer solar system planetesimal. This is our preferred explanation. It is dynamically plausible. It also provides a natural explanation for Pluto's high rock/ice ratio. Kinetic inhibition of equilibrium in the solar nebula favors the production of oxidized carbon and nitrogen compounds at the expense of methane and ammonia [3,9]. And if carbon is in the form of CO, enough oxygen is taken up that the rock/ice ratio is raised to ~ 70/30 [10,11]. Assemblage of outer solar system planetesimals from pre-solar grains may give a similar result. Pluto may be the first major solar system object for which the kinetic inhibition argument applies. In fact, its rock/ice ratio is so high that carbon may need to be in the form of CO_2 (as it apparently is in Halley). Competing uncertainties are the graphite and organic carbon fraction and the effect of Charon's formation. Finally, we note that the presence of CH_4 on Pluto's surface is not an argument against CO or CO_2; the methane could have been produced by the thermal metamorphism of organic material in Pluto's core.

*REFERENCES: [1] Tholen, D.J., and M.W. Buie (1987) Bull. Am. Astron. Soc. **19**, 859-860. [2] Mueller, S., and W.B. McKinnon (1988) Icarus, in press. [3] Prinn, R.G., and B. Fegley (1981) Astrophys. J. **249**, 308-317. [4] Friedson, A.J., and D.J. Stevenson (1983) Icarus **56**, 1-14. [5] McKinnon, W.B. (1984) Nature **311**, 355-358. [6] Ahrens, T.J., and J.D. O'Keefe (1985) in Ices in the Solar System, Proc. NATO Adv. Res. Conf., 631-654. [7] Stevenson, D.J., A.W. Harris, and J.I. Lunine (1986) in Satellites (Univ. Ariz. Press), 39-88. [8] Weidenschilling, S.J. (1981) Icarus **64**, 124-126. [9] Lewis, J.S., and R.G. Prinn (1980) Astrophys. J. **238**, 357-364. [10] Stevenson, D.J. (1984) in Uranus and Neptune, NASA CP-2330, 405-423. [11] McKinnon, W.B. (1985) in Ices in the Solar System, Proc. NATO Adv. Res. Conf., 829-856.*

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